Island-trapped waves, internal waves, and island circulation

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LONG-TERM GOALS

To understand oceanic flow around islands and to better predict them using basin-scale observations.

OBJECTIVES

The objective is to understand flow around large and small (with respect to the Rossby radius) topographic obstacles in the North Equatorial Current (NEC) and in the North Equatorial Countercurrent (NECC). For large islands, boundary currents are expected, but it is unclear what role integrated upstream conditions play versus episodic mesoscale eddy arrivals at the topography. As strong flows encounter small islands, points, and submarine ridges, it is expected that wakes, eddies, and arrested internal lee waves will be generated. The question is whether energy and momentum are lost in appreciable amounts due to encounters between low-frequency flows and topographic features that are not well/explicitly resolved in regional models. This would happen through a combination of (i) quasi-linear processes (e.g. form drag, lee waves, eddy generation) over small-scale topographic features and (ii) fundamentally nonlinear processes (turbulent island wakes).

APPROACH

Cruises in 2013 and 2014 obtained spatial surveys of currents and hydrography. These surveys were made with SeaSoar, which was towed from R/V *Revelle*. Currents (denoted u and v, which are positive east- and northward), potential temperature (θ), and salinity (S) were obtained from *Revelle*'s Doppler sonars and SeaSoar (an undulating vehicle equipped with a conductivity-temperature-depth instrument or CTD). SeaSoar completes a dive cycle from 5–400 m every $\sim$10 minutes or $\sim$3 km while being towed at 8 knots. Shipboard Doppler sonars included the Hydrographic Doppler Sonar System (HDSS) with 50 and 140 kHz systems for profiling to $\sim$700 and 300 m as well as an RDI Ocean Surveyor (OS) 75 kHz acoustic Doppler current profiler (ADCP) and a narrowband 150 kHz ADCP. The OS75 was operated in narrowband mode only to provide better statistics over its maximum depth range. In 2013, an underway CTD (UCTD) was used, which is described in detail in another annual report.

From 9 October to 12 November 2015, another SeaSoar cruise on *Revelle* will focus on wakes and arrested lee waves near Yap Island in the Federated States of Micronesia and the north/south points of the main islands of Palau as a contribution to the Flow Encountering Abrupt Topography (FLEAT) DRI.

WORK COMPLETED

Graduate education

Celia Ou, a graduate student starting her third year, has quality controlled the data from the 2013 and 2014 cruises and is focusing her analysis on the arrested lee waves with the intention of presenting these results at the Ocean Sciences meeting in 2016. These data will form the basis of her thesis.

In addition, 4 other Scripps graduate students will be joining the 2015 cruise as watch standers to gain at sea experience.

Cruise preparation

A new tow cable was faired over 2 weeks by Scripps Shipboard Technical Support (STS) and graduate students who are joining the upcoming cruise. Two complete SeaSoar units and ancillary gear were prepared and shipped recently to Palau for the upcoming cruise by STS.

Outreach

We will provide tours of *Revelle* to high school students and the US ambassador to Palau. Capt. Murline has expressed ongoing interest in these activities. These tours are being coordinated with the Coral Reef Research Foundation (CRRF), a research organization in Palau.

Cory Tamler, a writer, will be joining the cruise, participating in the work, and using this experience as a basis for a writing project.

RESULTS

Arrested lee waves

During the 2014 cruise, a strong eastward current was incident on Merir Island and adjacent submarine ridge. Arrested lee waves emanated from the topography and persisted over several days, during which three surveys were made.

Objective maps in the horizontal plane were made of the density data from SeaSoar and currents from the OS75 ADCP. Isopycnals show lee waves with a wavelength of about 15 km (Figure 1; Baines, 1995). The waves are present throughout the survey area, but mostly upstream/west of the topography. Upward and upstream phase propagation of the lee waves is found in both isopycnals and velocities.

Flux is calculated by considering the wave perturbations to the upstream mean conditions. Considerable westward flux is noted below 150 m, where the arrested lee waves are most prominent (Figure 2). Calculations of vertical flux (i.e., the energy extracted from the mean flow and delivered to the waves) are in progress.

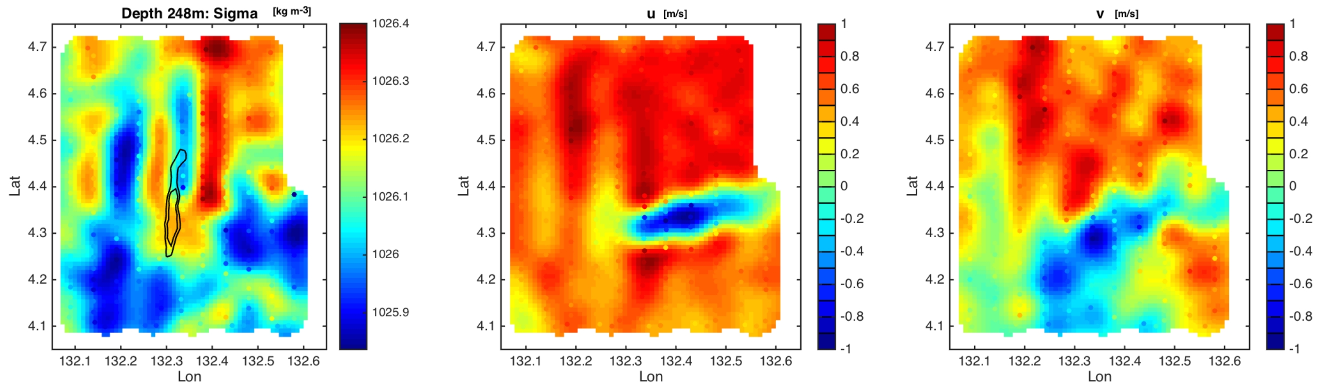

***Figure 1:** Objective maps of density and velocity were made on a 1 km by 1 km grid at a depth of 248 m, with an assumed decorrelation scale of 5 km. Black contours outline the shape of the submarine ridge near Merir Island at 800 m and 1000 m depth. Left: Upstream propagation of arrested internal lee waves is seen in potential density west of Merir. Middle: Strong eastward flow in the NECC and a wake in the lee of Merir is seen in zonal velocity. Right: flow divergence around the island is found in meridional velocity. Colored dots show observations before mapping in all panels.*

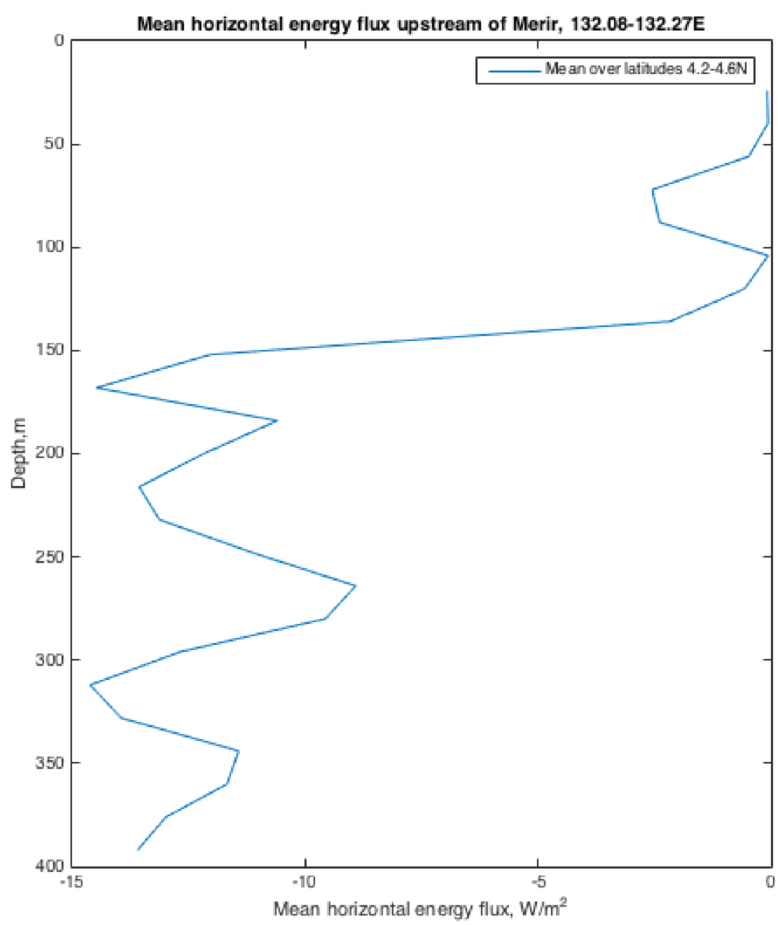

***Figure 2:** Horizontal flux is westward below 150 m and near zero above that. Flux is calculated from wave perturbations to the mean flow in the upstream region.*

Island wake

Large vertical current shear is found in the wake of Merir Island and may lead to turbulence. Furthermore, lateral gradients in the currents are roughly 2 m s^{-1} over 10 km (Figures 1b–c), which is about 20 times the local Coriolis frequency. This result indicates large Rossby number, strain, and vorticity in the wake, all of which suggest nonlinear phenomena in island wakes (Chang et al., 2013).

IMPACT/APPLICATIONS

While internal tides have energy conversion rates of $\mathscr{O}$(100 mW m^{-2}) in the western Pacific, little energy is lost from the barotropic tide in the vicinity of Palau (Egbert and Ray, 2003). However, geostrophic flow over the abrupt topography may input $\mathscr{O}$(0.1–100 mW m^{-2}) into lee waves in a patchy pattern below 10°N in the waters of Palau and the Federated States of Micronesia according to estimates by Nikurashin and Ferrari (2013). The lee wave energy estimates are based on modelled geostrophic flow and Smith-Sandwell bathymetry, which may underestimate the roughness on the scales of rough topography in the western Pacific (Smith and Sandwell, 1997). "Their theoretical argument for the global importance of lee-wave breaking is provocative and intriguing. However, the quantitative part of their conclusion is subject to several uncertainties. The largest issue is the paucity of direct observations of lee-wave generation, propagation and turbulent breaking in the deep or abyssal ocean," notes (MacKinnon, 2013). Further analysis of the these data may help with understanding how relevant lee wave generation and propagation are in this region of rough topography (i.e. tall, isolated seamounts and ridges that extend into the thermocline). Unlike the Southern Ocean where the lee waves occur over much smaller abyssal hill topography, the western Pacific contains more isolated, tall submarine topography- i.e., seamounts and ridges, which extend into the thermocline. Lee wave effects may be quite important locally, but not resolved or visible on a global map.

RELATED PROJECTS

There are a number of related projects: (a) state estimates of the tropical Pacific are being made (Bruce Cornuelle, SIO; Brian Powell, UH), (b) coastal measurement arrays around Palau have been deployed (Eric Terrill, SIO), and (c) gliders have repeated cross-shore sections around Palau (Dan Rudnick, SIO). All of these datasets and the cruise data will be useful for producing state estimates in the tropical Pacific and assessing the importance of lee waves and island wakes. The state estimates will also be essential for understanding how boundary currents depend on the upstream conditions via an island rule calculation (Godfrey, 1989) versus episodic eddy arrivals at a topographic obstacle.

The 2015 cruise is funded under the Flow Encountering Abrupt Topography (FLEAT) project and will focus on the arrested lee waves and wakes at three locations (Yap and north and south points of the main islands of Palau) to assess how commonly they occur. Cornuelle and Brian Powell (UH) will provide results from state estimates to help guide sampling during this cruise.

A DURIP award was received for UCTD system, which will be deployed regularly as a component of FLEAT from CRRF's coastal research vessel in 2016-17 to make spatial surveys of eddies and wakes generated at points in conjunction with the remotely-operated surface sampler (ROSS; Jonathan Nash, OSU) and the coastal measurement array (Terrill).

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